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(54) Method for surface erosion of superalloys employing a liquid jet

(57) A liquid jet is employed to roughen the surface of a substrate so as to enable a subsequent thermal spray coating material to adhere tightly to the surface. The substrate is preferably a superalloy that is either nickel, titanium or cobalt based. The method initially provides a high pressure liquid jet and moves the liquid jet across the substrate surface at a rate so as to deliver liquid to the surface in a range of amounts of at least approximately 0.7 kg/cm^2 to approximately 5.5 kg/cm^2. The high pressure liquid jet is preferably provided from a reservoir that is maintained at a pressure in the range of approximately 28 ksi to 52 ksi. A preferred embodiment employs an initial blast of a grit to the surface of the substrate to remove a smooth finish from the substrate, prior to the application of the liquid jet. The initial grit blast enables substantially lessened pressures and amounts of applied liquid mass to accomplish desired ranges of surface roughening.

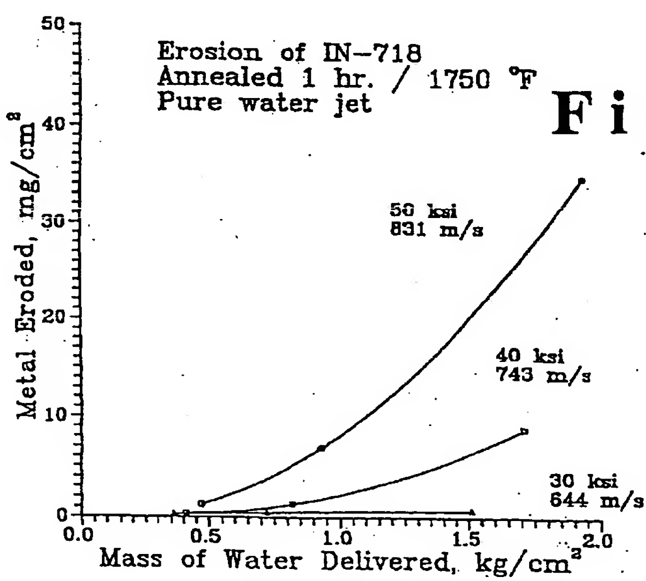


Fig. 1

EP 0 750 054 A1

Description

FIELD OF THE INVENTION

This invention relates to a method for applying thermal spray coatings to superalloys and, more particularly, to a method for preparing a surface of the superalloy to enable the thermal spray coating to adhere rigidly thereto.

BACKGROUND OF THE INVENTION

In general, metallic substrates which are to be coated by a thermal spray coating process are initially roughened by a grit blast to achieve a surface roughness which enables a good mechanical bond to be achieved. The grit blast, by its nature, leaves a residue of grit inclusions within the substrate. The grit material may include silicon carbide and iron particles, but in most applications is comprised of angular aluminum particles. Silicon carbide is no longer employed for grit blasting of high temperature superalloys due to concerns of forming low-melting phases which possibly affect stress/rupture life. Today, substantially all grit blasting is performed using alumina particles. The term "superalloy" includes cobalt, titanium and nickel-based alloys which exhibit both high strength and hardness levels.

For some applications, grit inclusions present a concern. Interface specifications, between a superalloy substrate and the coating, limit the amount of included grit. The coatings of turbine blades for use in aircraft engines must meet highly stringent interface inclusion limitations. Thus, the prior art has had to conform to the grit inclusion limits, while achieving a desired level of surface roughness to assure a rigid bond for a subsequently applied coating.

While a superalloy must exhibit a proper surface roughness to achieve a well bonded thermal spray coating, the surface must also be clean. Thus oils, grease and surface oxides, such as might be obtained from a prior pretreatment, are to be avoided. The prior art has achieved clean substrates by requiring use of a wet abrasive cleaning process which also adds fine grit inclusions to the superalloy surface. As the wet abrasive cleaning process was followed by a dry grit blast process, the combination added significant inclusions, i.e., up to 15% of the interface level. The presence of alumina grit inclusions on an otherwise clean interface has been found to allow reactions to occur during a subsequent heat treatment which result in undesirable interface decoration.

Accordingly, it is an object of this invention to provide an improved method for achieving a level of surface roughness of a superalloy wherein grit inclusions are avoided.

It is a further object of this invention to provide an improved method for roughening a surface of a superalloy by employing a high pressure liquid jet.

SUMMARY OF THE INVENTION

A liquid jet is employed to roughen the surface of a substrate so as to enable a subsequent thermal spray coating material to adhere tightly to the surface. The substrate is preferably a superalloy that is either nickel or cobalt based. The method initially provides a high pressure liquid jet and moves the liquid jet across the substrate surface at a rate so as to deliver liquid to the surface in a range of amounts of at least approximately 0.7 kg/cm^2 to approximately 5.5 kg/cm^2. The high pressure liquid jet is preferably provided from a reservoir that is maintained at a pressure in the range of approximately 28 ksi to 52 ksi. A preferred embodiment employs an initial blast of a grit to the surface of the substrate to remove a smooth finish from the substrate, prior to the application of the liquid jet. The initial grit blast enables substantially lessened pressures and amounts of applied liquid mass to accomplish desired ranges of surface roughening.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a plot of metal erosion versus mass of water delivered, showing erosion of IN-718 for reservoir-pressures of 30 ksi, 40 ksi, and 50 ksi.

Fig. 2 is a plot of metal erosion versus mass of water delivered, showing erosion of aged IN-718 for reservoir pressures of 30 ksi, 40 ksi, and 50 ksi.

Fig. 3 is a plot of metal erosion versus mass of water delivered showing erosion of a grit blasted IN-718 for reservoir pressures of 30 ksi, 40 ksi, and 50 ksi.

Fig. 4 is a plot of metal erosion versus water jet pressure for IN-718, showing a comparison between a grit blast surface and a surface which has not been grit blasted.

Fig. 5 is a plot of erosion weight loss versus mass of water delivered for a variety of superalloys from a reservoir maintained at 50 ksi.

Fig. 6 is a plot of metal erosion versus mass of water delivered for MAR-M 509 from a reservoir maintained at 32 ksi, 40 ksi, and 52 ksi.

Fig. 7 is a plot of erosion weight loss versus mass of water delivered, showing erosion of RENE 80 for a reservoir maintained at 40 ksi and 50 ksi.

Fig. 8 is a plot of surface roughness versus erosion weight loss for RENE 80 under the conditions shown in the plot of Fig. 7.

Fig. 9 is a plot of erosion weight loss versus mass of water delivered for 3 steel samples by a water jet from a reservoir maintained at 50 ksi.

Fig. 10 is a plot of threshold pressure versus hardness to achieve an initial erosion by a water jet of IN-718, MAR-M 509 and RENE 80.

Fig. 11 is a plot of mass of water delivered versus water jet pressure to achieve a 4.5 mg/cm^2 erosion for both cobalt-based and nickel based superalloys.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A high pressure waterjet is used to roughen a superalloy's surface in preparation for a subsequent thermal spray coating. The objective is to reduce to a minimum, interface inclusions in the superalloy surface from the roughening step. In many waterjet applications, such as cutting of metals or ceramics, abrasive material is added to the high pressure waterjet and dramatically enhances its cutting rate. This invention employs no abrasives in the waterjet, only a pure liquid that has been filtered and cleaned by reverse osmosis.

As will be apparent from the data below, it has been determined that a pure waterjet exhibiting a requisite pressure can provide sufficient surface erosion of a superalloy (or other metal) with little or no surface inclusions which adversely affect a later-applied thermal spray coating. In addition to enabling surface erosion, the waterjet spray further provides a cleaning action on the substrate surface.

The principal findings of this invention are as follows:

1. A critical minimum or threshold waterjet pressure is required to erode superalloys and other metals. The threshold waterjet pressure varies with the hardness of the substrate.

2. A minimum amount of water (or other liquid) must be delivered, and exceeded, for measurable erosion to occur in the substrate. Until that amount of water has been delivered, no measurable erosion occurs. The period before which erosion begins is termed the "incubation period".

3. It has been found that a light grit blast pretreatment to remove the surface finish of the substrate substantially accelerates a subsequent waterjet erosion action. The light grit blast pretreatment eliminates the incubation period, enables lower waterjet pressures to be employed and reduces the threshold waterjet pressure to achieve a desired level of erosion.

The useful range of waterjet erosion of a substrate is when an adequate level of roughness has been obtained, with a minimum of substrate removal. The roughness minimum required for a thermal spray coating is approximately 80 microinches and in one superalloy (i.e. IN-718) is achieved at approximately 5 mg/cm^2 removal (approximately 1/4 mil of thickness of the substrate). The roughness maximum for a subsequent thermal spray coating is approximately 500 microinches due to self masking and shadowing of a subsequent thermal spray coating and, thus, incomplete coverage at the interface and reduced bond strength.

In order to achieve an adequate roughening of the surface, it has been determined that an average thickness removal minimum is approximately 0.2 mils, which corresponds to a removal of approximately 4.5 mg/cm^2 of a typical superalloy surface. The maximum thickness removal that can be accepted is approximately 2 mils. This limit is based on a concern for the reduction in cross section of a thin wall superalloy used for turbine blade applications. Such a thickness removal corresponds to approximately 45 mg/cm^2 erosion of the substrate surface. It has further been determined that an adequate and useful roughness for a subsequent thermal spray coating is approximately 160 microinches and is obtained in IN-718 at 10 mg/cm^2 erosion.

To achieve a roughened superalloy surface suitable for a subsequent thermal spray coating, the preferred ranges of roughness, erosion and thickness loss are as follows:

roughness - 50-500 micro inches;
erosion - 4.5-45 mg/cm^2; and
thickness loss - 0.25-2.0 mls.

The more preferred ranges of roughness, erosion and thickness loss are as follows:

roughness - 80-200 micro inches;
erosion - 5-20 mg/cm^2 and
thickness loss 0.25-1.0 mls.

The above ranges can be achieved by application of a pure waterjet that is scanned across the surface in a raster manner. The waterjet must exhibit a pressure that is at least above the threshold pressure for the alloy being roughened. Further, the scan rate of the waterjet is set so that the mass of water applied per unit area is greater than a critical delivered amount.

It has further been found that a pretreatment by a light grit blast applied to the surface enables a more rapid surface roughening action by a subsequent waterjet application, with lower waterjet pressures.

As will be apparent from the data below, the invention has been tested on both nickel-based superalloys and cobalt-based superalloys which will be hereafter referred to by their trade names: IN-718; MAR-M 509 and RENE 80. The compositions of each of the aforementioned alloys (in weight %) is as follows:

TABLE 1

IN-718	
carbon	0.05
chromium	19
aluminum	0.5
titanium	1.0
molybdenum	3.0
niobium	5.0
zirconium	0.01
boron	0.005
iron	18

TABLE 2

MAR - M 509	
carbon	0.55 - 0.65
chromium	21.0 - 24.0
nickel	9.0 - 11.0
tungsten	6.5 - 7.5
tantalum	3.0 - 4.0
titanium	0.15 - 0.25
zirconium	0.40 - 0.60
manganese	0.10 max
silicon	0.40 max
boron	0.01 max
iron	1.50 max
sulphur	0.015 max
cobalt	remainder

TABLE 3

RENE 80	
cobalt	9.5
chromium	14
molybdenum	4
tungsten	4
titanium	5
aluminum	3
carbon	0.17
zirconium	0.03
boron	0.015
nickel	balance

EXPERIMENTAL

Experimental work was accomplished employing a Flow International Model 9X Pressure Intensifier capable of 358 MegaPascals (52 ksi) maximum water pressure. The waterjet was defined by a 0.4 mm (0.016 inch) diameter sapphire orifice and the stream was rastered across test substrates at various traverse speeds, but all with a common 0.76 mm (0.03 inch) offset between raster traces. The stand-off from the substrate surface to the jet exit nozzle was 7.6 cm (3 inches) throughout, which was found to be the distance for maximum erosion effect.

A single erosion trace had a width of approximately 1.5 mm (0.06 inches). The alloy substrates were weighed before and after waterjet exposure as well as their thicknesses were measured. The erosion was calculated as milligrams of mans lost, per square centimeter of surface area. Most of the samples were round buttons, 25.4 mm in diameter and 3.2 mm thick but some were of odd coupon dimensions, cut from turbine blade roots or sheet stock. The high pressure pump had the following water flow rates through the 0.4 mm orifice. At 207,276 and 345 MPa (30, 40 and 50 ksi) reservoir pressures: 3.49, 3.97, and 4.50 liters/minute.

From these flow rates and raster rate, the mass of water delivered to each specimen was calculated in kilograms per square centimeter.

An initial survey of the effect of the high pressure jet on various alloy coupons was performed at a 50 ksi reservoir pressure and a 30.5 cm/min. traverse rate. Based on these results, another mating specimen was run at either a faster or slower traverse rate, depending on whether the first erosion loss was relatively large or small. These multipoint data sets are shown in the Figs.

The IN-718 was solution annealed for one hour at 954°C (1750°F) and had a Rockwell B hardness of 103. The MAR-M 509 coupons were in an as - cast condition with a superficial Rockwell C hardness of 31.0. The RENE 80 coupon were cut transversely from a directionally solidified rod, which had been given a standard solution anneal of four hours at 1200°C in vacuum, with a final hardness of 39.4 HRc. The original MAR - M 509 surfaces were ground and then vibratory finished with triangular aluminum media in water, producing an initial surface finish of 0.5 micrometers. The RENE 80 was surface ground to a 0.3 micrometer finish. The eroded surfaces were examined on a scanning electron microscope and the roughness measured with a portable Taylor-Hobsen profilometer at a 0.76 mm (0.03 inches) cutoff setting.

Fig. 1 is a plot for IN-718 of mass of water delivered (in kg/cm^2) versus metal eroded (mg/cm^2). Two important features of the waterjet erosion process are evident from the plot of Fig. 1. One is that there is a minimum mass of water required to impinge on the IN-718 substrate before there is a measurable erosion, that is, an incubation period. Thus, at 40 ksi, substantial erosion does not occur until after 0.8 kg/cm^2 of water has been delivered across the substrate. At such time, erosion commences and increases in exponential fashion. At 50 ksi, the incubation period terminates at approximately 0.5 kg/cm^2.

The second feature is that there is a threshold pressure required for measurable erosion and that 30 ksi is only slightly above that threshold. The erosion threshold jet pressure can be determined from the initial slopes of the curves. It has been determined that a threshold for solution annealed IN-718 is approximately 28.5 ksi(196 MPa). From the Bernoulli equation, the threshold pressure can be converted to jet velocity, and thus the corresponding threshold velocity

for IN-718 is 650 meters per second.

In Fig. 2, similar erosion conditions were performed on an aged IN-718 coupon which had been annealed for one hour at 1750°F and then aged, for eight hours, at 1325°F plus an additional 10 hours at 1150°F. The aged IN-718 had a Rockwell B hardness of 115. Note that the metal erosion values were considerably less than those shown in Fig. 1, evidencing a distinct dependence upon substrate hardness.

The experiments shown in Fig. 1 were repeated, for an IN-718 coupon which had been subjected to a pretreatment of a light grit blast to remove the original smooth finish of the coupon (see Fig. 3). A 240 mesh angular alumina grit was employed with a blast head positioned 2 inches from the coupon at a 90° impingement angle. The applied grit pressure was 35 psig. Subsequent to the grit blast pretreatment, the coupon was subjected to a waterjet erosions at 30 ksi, 40 ksi and 50 ksi reservoir pressures. Note that in each case, a substantial increase in metal erosion value is evident at the respective waterjet pressures.

In Fig. 4, a direct comparison is shown between metal erosion values for a sample which was grit blasted and then subjected to a waterjet roughening procedure versus a portion of the same sample which was subjected to the waterjet roughening procedure, without the initial grit blast. In the plot of Fig. 4, the amount of metal erosion is plotted against waterjet pressure and it is to be noted that erosion commences at a considerably lesser pressure when the sample has been grit blasted as compared to the non-grit blasted sample.

In Fig. 5, the mass of water delivered to the substrate is plotted against erosion weight loss for a variety of materials which have been subjected to a 50 ksi waterjet roughening procedure. The IN-718 data discussed above (solution annealed 1hr at 1750°F) is plotted and erosion data for an IN-718 coupon in an over-solution condition (4hrs. at 1975°F) has been added as well as data for a sample of titanium - 6 wt. percent aluminum - 4 wt. percent vanadium. The titanium alloy behaved somewhat like the IN-718 (1 hr./1750°F), but the IN-718 (4 hrs./1975°F) exhibited a much higher erodability for a like mass of water delivered. As can be seen from the data plotted in Fig. 5, there was substantial difference in the erosion weight loss achieved in the IN-718 samples, depending upon the heat treatment state. For the case of waterjet erosion at 50 ksi, a 40 mg/cm^2 weight loss achieved a 7.5 micrometer roughness in IN-718 annealed 1 hr. at 1750°F, but a 11.5 micrometer roughness in the IN-718 annealed 4 hrs. at 1975°F. At the same jet pressure and mass of water delivered, the over-solution material had substantially more erosion loss and greater roughness.

The trend of MAR-M 509 erosion as a function of mass of water delivered to the substrate is shown in Fig. 6. The 359 MPa (52 ksi) erosion data curve increases exponentially with increasing mass of water impingement. A similar but still exponential curve is seen at 276 MPa (40 ksi), with both curves suggesting a threshold or incubation period occurring at the initiation of the erosion action.

In Fig. 7, the erosion of RENE 80 is shown in a plot of erosion weight loss versus mass of water delivered. Note that it is clearly seen that there is a threshold value of approximately 1 kg/cm^2 before measurable erosion occurs.

The surface roughness of the eroded RENE 80 coupons is shown in Fig. 8 as a function of erosion weight loss. The roughness rises quickly with erosion and then moves towards a limiting value of approximately 30 micrometers at a very high eroded weight loss. Recall that the 220 mg/cm^2 weight loss corresponds to approximately a 10.6 mil surface removal. This is substantially more than the modest surface removal required for thermal spray preparation. However, at a weight loss of approximately 10 mg/cm^2, it was found that a roughness of approximately 5 micrometers occurred which was quite adequate for a subsequent thermal spray application.

In Fig. 9, the results of waterjet erosion tests on steels having hardnesses of 40, 50 and 60 Rockwell "C" are shown. Here again, it is to be noted that the erosion weight loss is substantially dependent upon the hardness of the substrate, as well as the applied waterjet pressure and mass of water delivered.

To demonstrate that a substrate which has been subjected to a waterjet roughening procedure will provide a good base for a plasma spray coating, a nickel based superalloy turbine blade was cleaned and roughened in one step using appropriate waterjet parameters found above. The blade had a dark surface oxide originally, but it was removed completely by the waterjet roughening procedure. The erosion weight loss of the blade was 10.7 mg/cm^2, about 0.012 mm thickness removal. The blade was then coated with an MCrAlY overlay (where M is, nickel, cobalt or iron) by an argon shrouded plasma spray, heat treated in a vacuum, finished and peened. An excellent bond was obtained and the interface was absolutely clean everywhere.

The results above indicate that each tested substrate material exhibits a threshold pressure below which surface erosion does not commence. In Fig. 10, a plot is shown of threshold pressure versus hardness (Rockwell B) for the three principal superalloys that were studied, IN-718; MAR-M 509 and RENE 80. Note that as the hardness increases, the threshold pressure increases in an exponential fashion.

In Fig. 11, the mass of water delivered is plotted against waterjet pressure for both cobalt-based superalloys and nickel-based superalloys. In each case, the mass of water delivered was that required to achieve a 4.5 mg/cm^2 erosion of the substrate. Note that for cobalt-based superalloys, the mass of water delivered varies from approximately 0.7 kg/cm^2 at 52 ksi to 5.5 kg/cm^2 at approximately 31.5 ksi. By contrast, the nickel based superalloys exhibit a lesser mass of water required to achieve a similar erosion state and at lower waterjet pressures (e.g. approximately 1.5 kg/cm^2 at 40 ksi.

In summary, the above studies indicate that threshold waterjet pressures are present for each substrate material

below which erosion will not occur. Those pressure are shown in Table 4.

TABLE 4

THRESHOLD PRESSURE	
Material	Ksi
MAR-M 509	30.6
RENE - 80	36.2
IN-718	28.5

Table 5 below denotes the critical mass of water needed to achieve the stated levels of erosion in the variety of substrates subjected to test. Each of the entries in Table 5 establishes, for at least a minimum erosion level of 4.5 mg/cm^2, the mass of required water at the indicated pressure. Also, there is an entry (for all but one substrate) which indicates the mass of water required to achieve a maximum level of erosion of 45 mg/cm^2. The entries in Table 5 which have an asterisk are interpolated values between experimentally achieved values.

TABLE 5

CRITICAL MASS OF H_2O TO ACHIEVE STATED EROSION								
SUBSTRATE	EROSION (mg/cm$_2$)	Mass of H_2O (kg/cm$_2$) at Pressure (ksi)						
		30	32	40	41	44	50	52
MAR M 509	4.5		5.4		2.3*			0.7
	45		>12		12.4*			5.0
RENE 80								
Solution Anneal 4 hrs. (2200°F)	4.5			1.6			0.9	
	45			5.4			2.5	
IN-718								
Solution Anneal 1 hr. (1750°F)	4.5	>2		1.3			0.8	
	45	>>2		>2			2.2	
IN-718								
Solution Anneal 1 hr./1750°F w/ grit blast	4.5	1.5		0.8			0.45	
	45	>>2		2.55*			1.75	
IN-718								
Aged	4.5	>>2		2.1			1.3	
STEELS								
Rockwell C 40	4.5						1.8	
Rockwell C 40	45						3.6	
Rockwell C 50	4.5						2.0	
Rockwell C 50	45						5.8	
Rockwell C 60	4.5						4.2	
Rockwell C 60	45						>>12	

While the above description has been based upon the use of water as the jet erosion source, those skilled in the

art will realize that other pure liquids can be appropriately substituted. Such liquids are ethylene glycol, high density alcohols, polywater, etc.

It should be understood that the foregoing description is only illustrative of the invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the invention. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variances which fall within the scope of the appended claims.

Claims

1. A method for roughening a surface of a substrate, said method comprising the steps of:

a. providing a pre-roughening by a blast of grit across the surface of the substrate;
b. providing a liquid jet of at least 28 ksi pressure; and
c. moving said liquid jet across said surface of said substrate at a rate so as to deliver the liquid to said surface in a range on amounts between 0.7 kg/cm^2 and 5.5kg/cm^2.

2. The method of claim 1 wherein the following step is added:

a. depositing a layer of metallic, ceramic, or cermet material upon said surface using a thermal spray coating device.

3. The method of claim 1, wherein the jet pressure and the amount of liquid delivered to said surface is adjusted to roughen said surface to within a range of 50 - 500 microinches.

4. The method of claim 1, wherein the jet pressure and the amount of liquid delivered to said surface are adjusted to erode said surface to a thickness loss not exceeding 2.0 mils.

5. The method recited in claim 1, wherein said substrate is a superalloy selected from the group consisting of nickel based alloys, cobalt based alloys, iron based alloys, and titanium based alloys.

6. The method of claim 1, wherein said liquid jet comprises a flow of liquid selected from the group consisting of water, ethylene glycol, alcohols and polywater.

7. The method of Claim 2, wherein the thermal coating spray device is selected from the group consisting of plasma spray, detonation gun, high velocity oxy-fuel, and high velocity impact fusion.

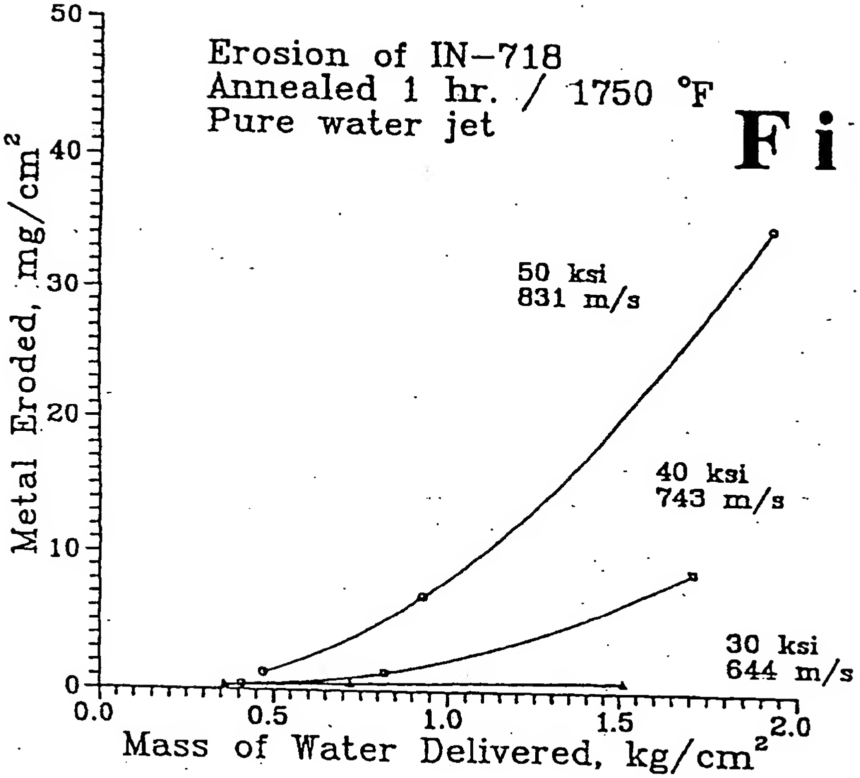
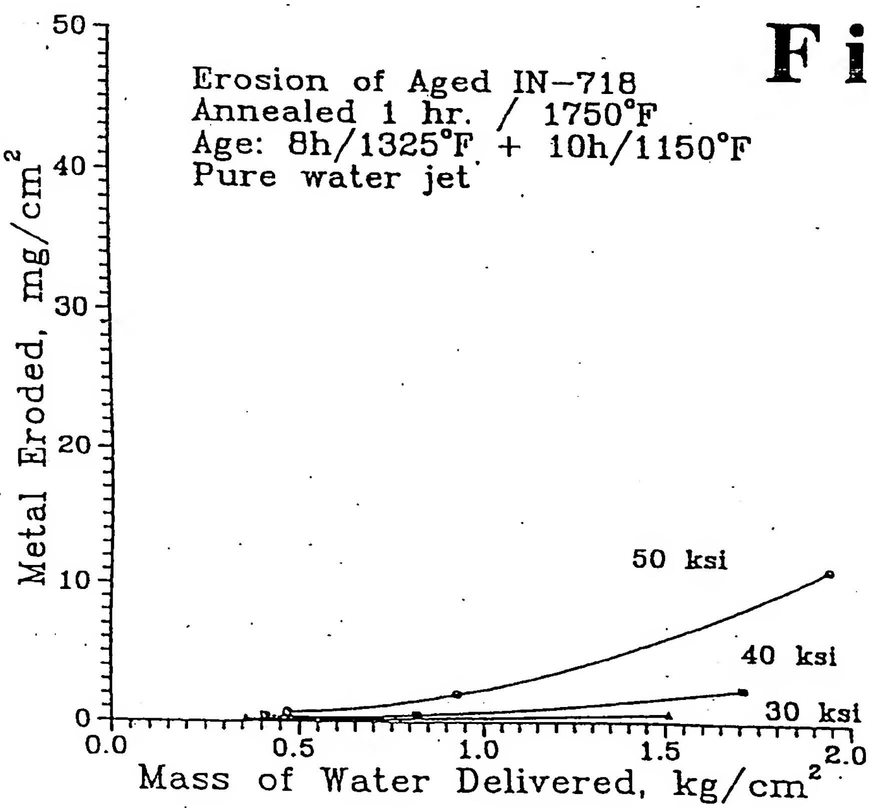

Erosion of IN-718
Annealed 1 hr. / 1750 °F
Pure water jet
50 ksi
831 m/s
40 ksi
743 m/s
30 ksi
644 m/s
Metal Eroded, mg/cm²
Mass of Water Delivered, kg/cm²
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

Fig. 1

Fig. 2


Erosion of Aged IN-718
Annealed 1 hr. / 1750°F
Age: 8h/1325°F + 10h/1150°F
Pure water jet
50 ksi
40 ksi
30 ksi
Metal Eroded, mg/cm²
Mass of Water Delivered, kg/cm²
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

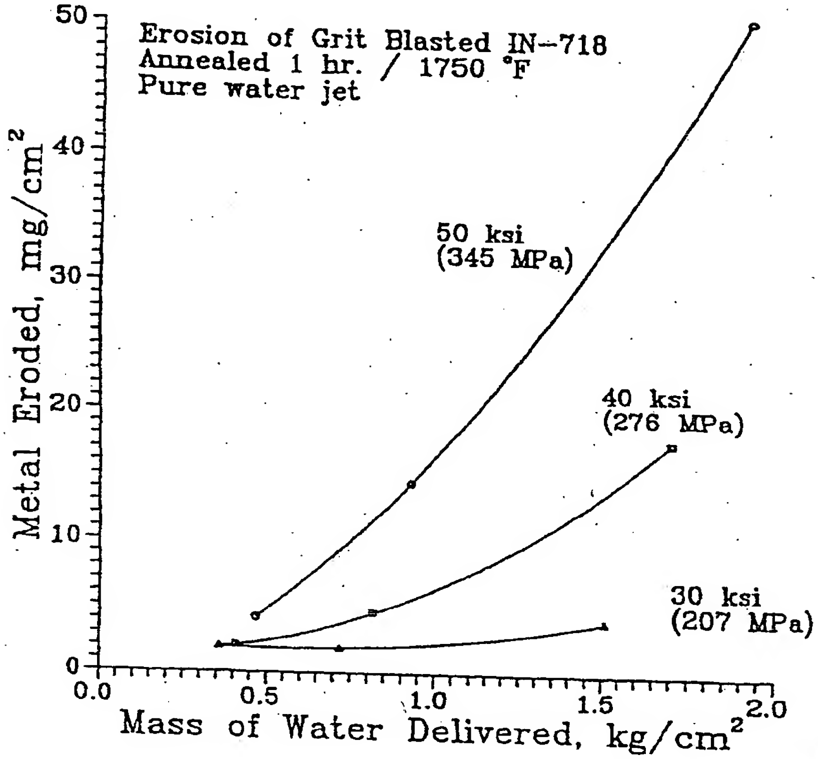

Erosion of Grit Blasted IN-718
Annealed 1 hr. / 1750 °F
Pure water jet
50 ksi
(345 MPa)
40 ksi
(276 MPa)
30 ksi
(207 MPa)
Metal Eroded, mg/cm²
Mass of Water Delivered, kg/cm²
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

Fig. 3

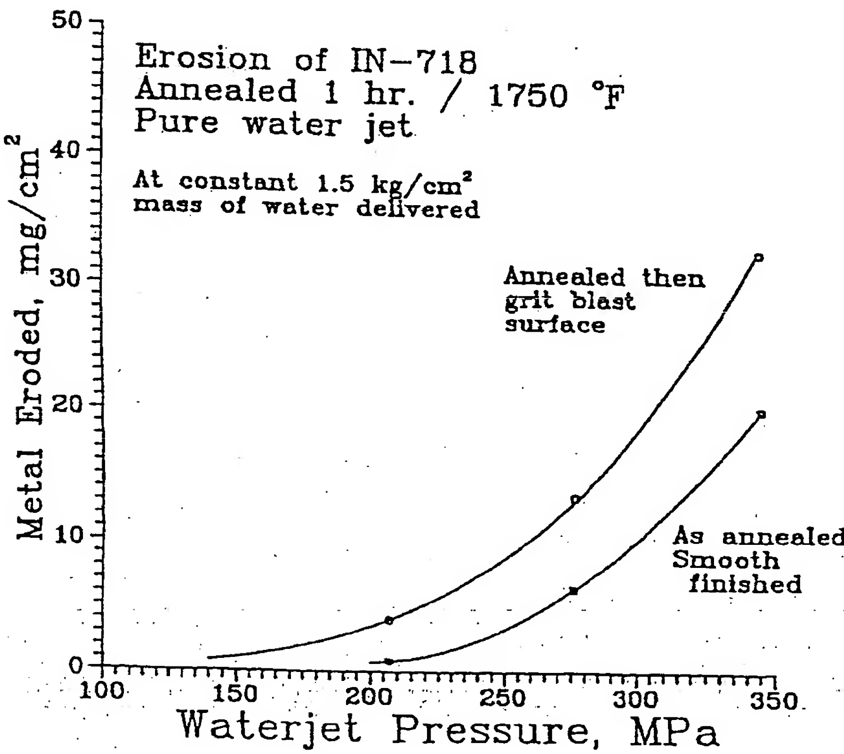

Erosion of IN-718
Annealed 1 hr. / 1750 °F
Pure water jet
At constant 1.5 kg/cm²
mass of water delivered
Annealed then
grit blast
surface
As annealed
Smooth
finished
Metal Eroded, mg/cm²
Waterjet Pressure, MPa
0
10
20
30
40
50
100
150
200
250
300
350

Fig. 4

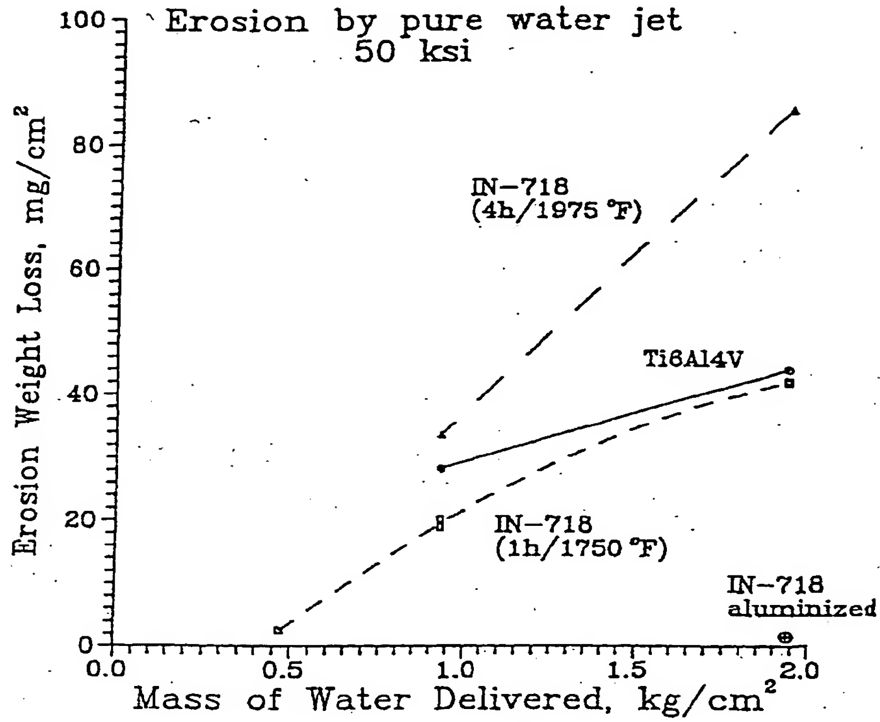

Erosion by pure water jet
50 ksi
Erosion Weight Loss, mg/cm2
IN-718
(4h/1975 °F)
Ti6Al4V
IN-718
(1h/1750 °F)
IN-718
aluminized
Mass of Water Delivered, kg/cm2
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0

Fig. 5

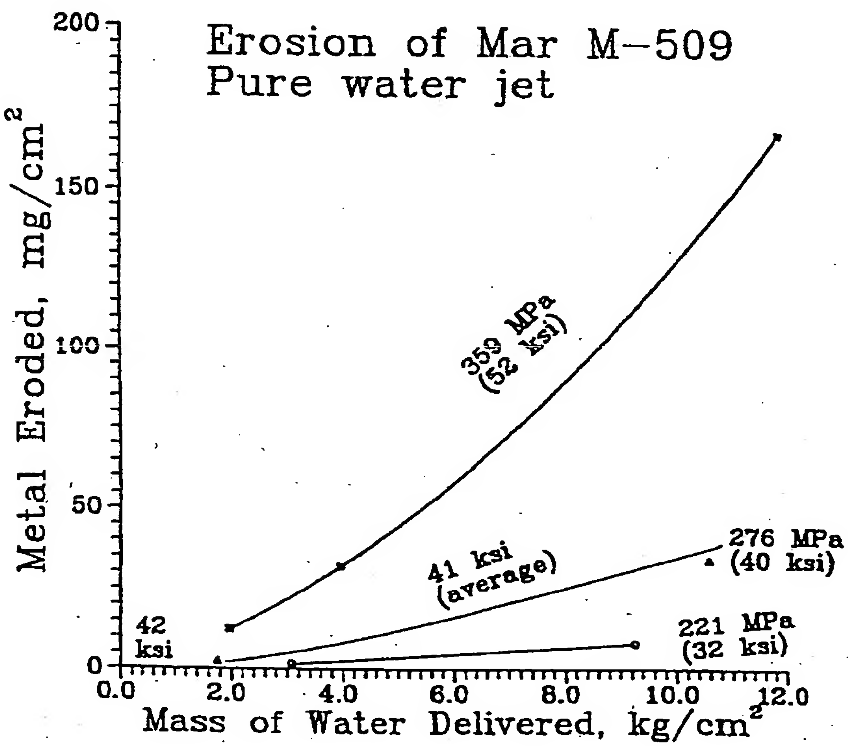

Erosion of Mar M-509
Pure water jet
Metal Eroded, mg/cm2
359 MPa
(52 ksi)
41 ksi
(average)
276 MPa
(40 ksi)
42
ksi
221 MPa
(32 ksi)
Mass of Water Delivered, kg/cm2
0
50
100
150
200
0.0
2.0
4.0
6.0
8.0
10.0
12.0

Fig. 6

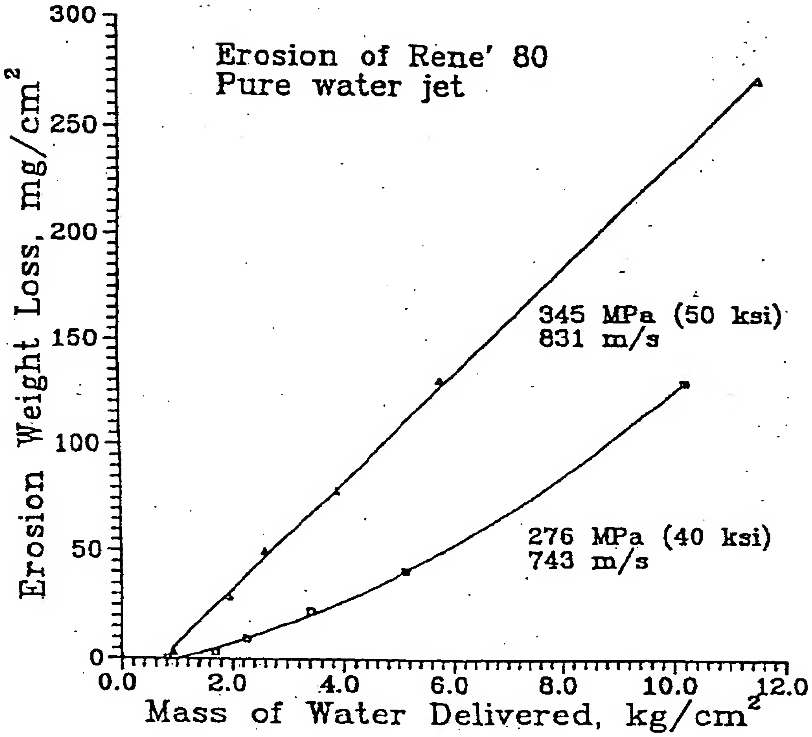

Erosion of Rene' 80
Pure water jet
345 MPa (50 ksi)
831 m/s
276 MPa (40 ksi)
743 m/s
Erosion Weight Loss, mg/cm^2
Mass of Water Delivered, kg/cm^2
0
50
100
150
200
250
300
0.0
2.0
4.0
6.0
8.0
10.0
12.0

Fig. 7

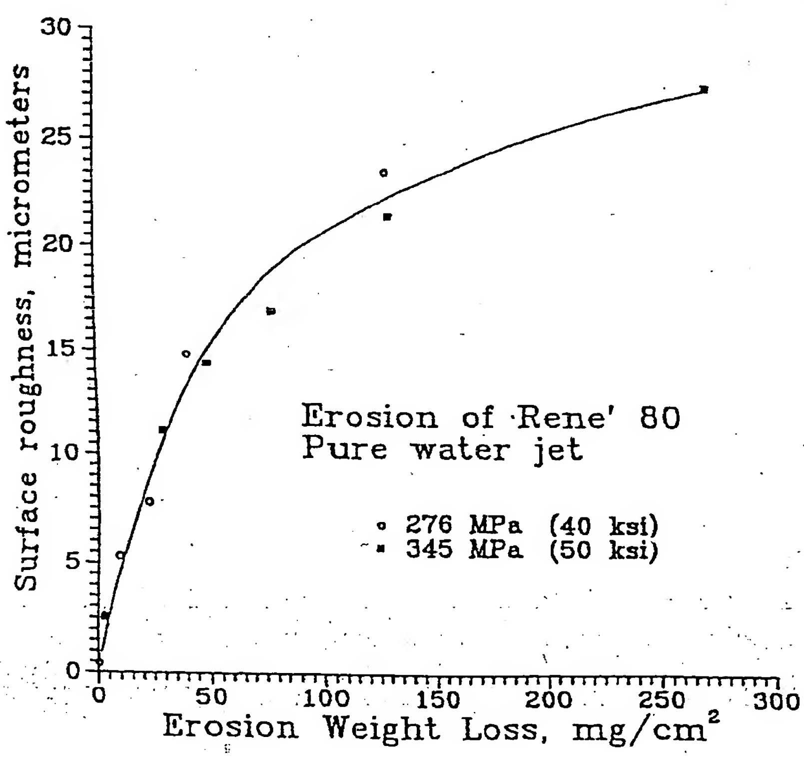

Erosion of Rene' 80
Pure water jet
276 MPa (40 ksi)
345 MPa (50 ksi)
Surface roughness, micrometers
Erosion Weight Loss, mg/cm^2
0
5
10
15
20
25
30
0
50
100
150
200
250
300

Fig. 8

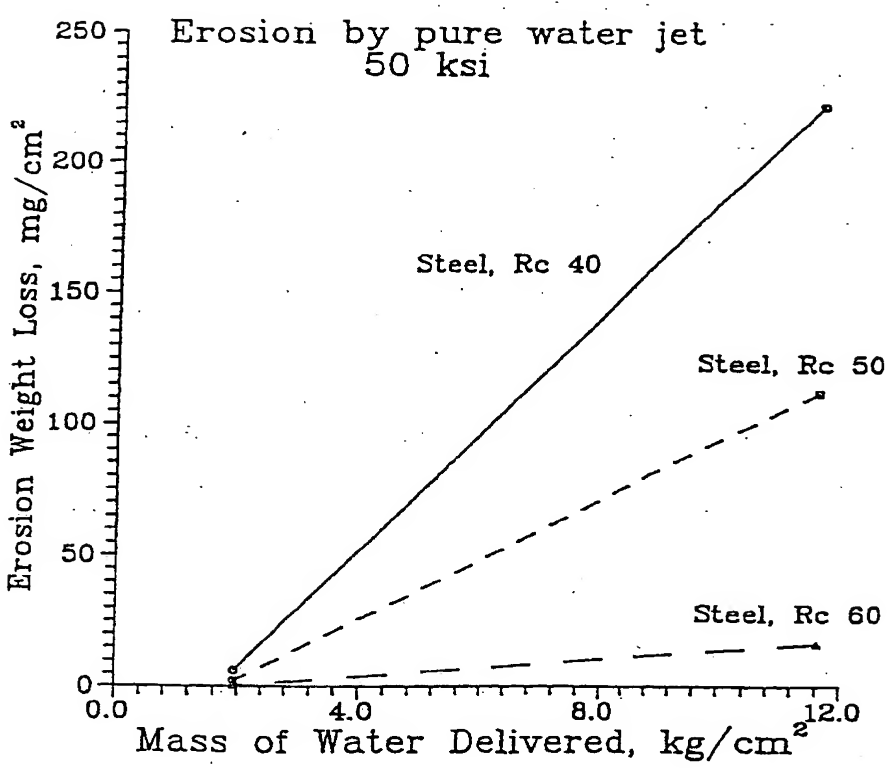

Erosion by pure water jet
50 ksi
Erosion Weight Loss, mg/cm²
250
200
150
100
50
0
Steel, Rc 40
Steel, Rc 50
Steel, Rc 60
0.0
4.0
8.0
12.0
Mass of Water Delivered, kg/cm²

Fig. 9

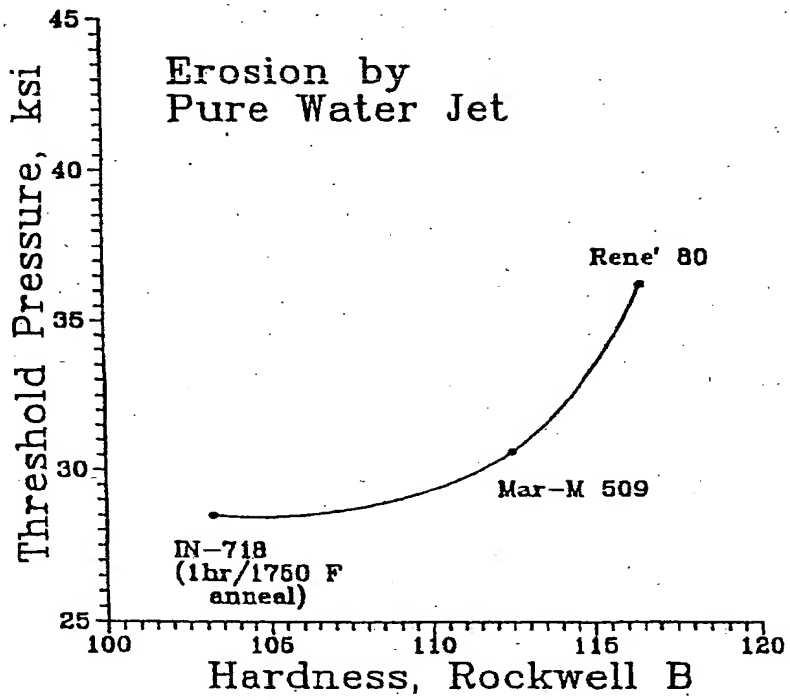

Erosion by
Pure Water Jet
Threshold Pressure, ksi
45
40
35
30
25
Rene' 80
Mar-M 509
IN-718
(1hr/1750 F
anneal)
100
105
110
115
120
Hardness, Rockwell B

Fig. 10

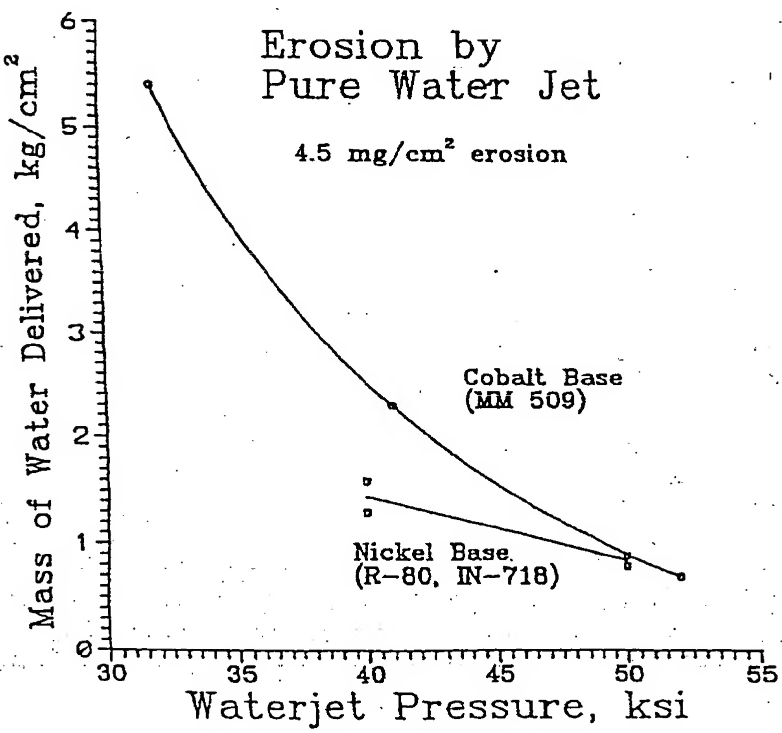

Erosion by
Pure Water Jet
4.5 mg/cm² erosion
Mass of Water Delivered, kg/cm²
6
5
4
3
2
1
0
Cobalt Base
(MM 509)
Nickel Base
(R-80, IN-718)
30
35
40
45
50
55
Waterjet Pressure, ksi

Fig. 11

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EP 96 10 9797

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	EP-A-0 618 040 (FUJI OOZX INC.) * claims 1-5 *	1,2,7	C23C4/02 B24C1/00
Y A	EP-A-0 568 315 (VANKUIKEN LEWIS) * claims 6-11 *	1,2,7 3,4,6	
A	FR-A-2 413 225 (SOCIETE NOUVELLE DE METALLISATION) * page 1, line 23 - line 39; claims 1,8,9,13 *	1,2,7	
A	US-A-5 128 172 (THOMAS E. WHITTICK) * column 4, line 57 - column 5, line 9; claims 1-6 *	1,2,7	
A	DE-A-40 32 862 (BERGMANN-BORSIG) * column 2, line 25 - line 49; claim 1 *	1-3,6,7	
A	PATENT ABSTRACTS OF JAPAN vol. 9, no. 172 (M-397), 17 July 1985 & JP-A-60 044267 (TOYOTA JIDOSHA), 9 March 1985, * abstract *	1,2,7	TECHNICAL FIELDS SEARCHED (Int.Cl.6) C23C B24C
A	PATENT ABSTRACTS OF JAPAN vol. 7, no. 77 (C-159), 30 March 1983 & JP-A-58 009972 (KANSAI METARIKON KOGYOSHO), 20 January 1983, * abstract *	1,2,7	
A	PATENT ABSTRACTS OF JAPAN vol. 18, no. 380 (M-1639), 18 July 1994 & JP-A-06 106213 (KAWASAKI STEEL CORP), 19 April 1994, * abstract *	1,6	
A	EP-A-0 245 602 (ALFRED TEVES) * claims 1-4 *	1,6	
	-/--		

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	19 September 1996	Elsen, D

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Application Number
EP 96 10 9797

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	EP-A-0 509 536 (EDWARDS,KNIESE &CO HOCHVACUUM) * claims 1-8 * -----	1,6	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

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